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NIST Manufacturing Research and Services

The job of the U.S. Commerce Department's National Institute of Standards and Technology is to help the nation's manufacturers—and other parts of the U.S. economy—create and capitalize on technological opportunities. For nearly a century, NIST has been working with companies of all sizes and with industries of nearly every type to develop and apply technology, measurements, and standards. Programs added over the last decade have extended and diversified NIST's efforts, strengthening it as a source of technological advantage for the nation's manufacturing sector. (See Snapshot of NIST Programs, p. 2.) Here are a few recent examples:

- *Five- to 10-year head start in early-stage research.* That's one of several major benefits that U.S. makers of coordinate measuring machines (CMMs) attribute to NIST's pioneering work on software-based methods for improving machine-tool accuracy. The technology enabled these manufacturers to produce lower-cost designs without compromising CMM performance. Production-efficiency gains ranged from 10 percent to 30 percent. Software-based accuracy enhancement methods have been extended to piston-turning machines and other machine tools now on the market. And a new, widely applicable method for estimating cutting errors—machining variation analysis, which NIST developed jointly with researchers from the Massachusetts Institute of Technology—already has been used by U.S. firms to improve the design of machine tools and processes.
- *Enabled hundreds of innovations in printed wiring board (PWB) technology.* This accomplishment is credited to an industrial collaboration made possible by a cost-shared, competitively awarded cooperative agreement with the NIST Advanced Technology Program (ATP). ATP-enabled advances are spreading throughout the nation's $7 billion PWB industry, helping it to reverse a steep drop in global market share—from about 40 percent in the mid-1970s to 27 percent in 1991. In a five-year research effort, companies joined together to effectively attack a broad array of fundamental technical issues in PWB manufacturing. According to the president of the National Center for Manufacturing Sciences, the ATP-enabled research effort "quite literally saved an industry and shaped an unprecedented process for the performance of cooperative research and development."
- *More competitive, more capable small and medium-sized manufacturers.* Reduced cycle times, more efficient plant layouts, smaller inventories, increased productivity, and improved bottom lines. ... These are the kinds of operational and business benefits that smaller U.S. manufacturers are realizing through the services of NIST's Manufacturing Extension Partnership, a nationwide network of more than 400 technical assistance centers and offices.
- *"... an extensive competitiveness education network."* That's how the president of the National Alliance for Business described the Malcolm Baldrige National Quality Award, managed by NIST in cooperation with industry. Especially in the manufacturing sector, the award program has been a powerful catalyst

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Snapshot of NIST Programs (www.nist.gov)

■ NIST's Measurement and Standards Laboratories provide technical leadership for vital components of the nation's technology infrastructure. They develop broadly useful tools, such as high-accuracy, ultra-precise measurement methods, whose value grows as they are diffused as standards across groups of companies and even entire industries.

■ The Advanced Technology Program, a competitive, cost-shared awards program for U.S. industry, fosters and accelerates early-stage development of high-risk technologies that, down the road, promise significant commercial pay-offs and widespread benefits for the economy.

■ The Manufacturing Extension Partnership, a nationwide network of technical and business assistance centers, helps smaller manufacturers to identify and implement modern production techniques, innovative workforce practices, electronic-commerce tools, and other technologies crucial to their competitiveness, today and tomorrow.

■ The Baldrige National Quality Program encourages and assists U.S. businesses, educational organizations, and healthcare providers in their performance and quality improvement efforts through its management, with U.S. industry, of the Malcolm Baldrige National Quality Award and through its active dissemination of the award program's framework, core values, criteria, and assessment methods.

for continuous improvement. An executive at the Solectron Corp., a two-time winner in the manufacturing category, says the award criteria are a "template for process improvement as well as for driving leadership and employee involvement in all aspects of quality."

In the technology arena of the fiercely competitive global economy, NIST's programs and its staff of 3,300 are helping to speed the pace of innovation, ensure the mastery and application of new technology, and advance U.S. technical interests in the increasingly important realm of international standards.

Only NIST

"NIST is the only agency which provides the infrastructure that industry needs to commercialize civilian technologies that drive the U.S. economy."

—Arpad A. Bergh, President
Optoelectronics Industry Development Association

"NIST is the only place in the U.S. where the broad range of measurements needed for semiconductor processing are routinely and systematically developed."

—Semiconductor Industry Association

NIST occupies a unique niche in the nation's technology infrastructure. It is helping to build an essential foundation for technological progress and industrial growth: technical services and tools, industrial modernization assistance, quality-promotion efforts, and risk-sharing incentives that motivate U.S. companies to pursue next-generation manufacturing technologies. In this behind-the-scenes role, NIST complements private-sector efforts. It focuses on important technical tasks that are prone to underinvestment either because the resulting benefits are broadly shared or because the risks and planning horizons exceed the thresholds of individual firms.

NIST's four major programs are highly leveraged. Most projects are planned and carried out with industry, often yielding industry-wide benefits.

Measurements and Standards for Competitiveness

" 'NIST quality' measurements link all U.S. companies and institutions to the rest of the global economy."

—William E. Gittler and Doug Vohden
Scott Specialty Gases, Inc.

In every industry, firms rely on a toolkit of supporting, generic technologies. Integral to a company's manufacturing capabilities, these indispensable tools range from tables of scientific and engineering data to statistical quality-control methods to measurement techniques for ensuring that one coordinate measuring machine's micrometer is the same as another CMM's micrometer.

Specializing for nearly 100 years in the critical area of measurements and standards, NIST's seven Measurement and Standards Laboratories are key suppliers of such infrastructural technologies and services. (See In a Capsule: NIST Services.) The results of NIST research lead to industry-accepted test and measurement methods, process models, interface standards, and other useful tools. In industries ranging from electronics to radio-pharmaceu-ticals and from chemical processing to aerospace, these tools contribute to effective operations and quality products. The capabilities that they support often set the technical limits on what can be accomplished on the factory floor, in the R&D laboratory, or with suppliers and customers.

Consider the U.S. automotive industry, a long-standing customer of NIST measurement services, or the fast-growing optical-fiber industry. About 350 NIST-developed Standard Reference Materials—the equivalents of certified "rulers" that firms use to check the accuracy of their own measurements—support motor-vehicle production at nearly every step of the process, from the manufacture of sheet metal, windshields, tires, and transmission gears to final assembly.

In the optical-fiber industry, technical contributions made by NIST's Measurement and Standards Laboratories serve as the basis for more than two dozen standardized measurement methods that U.S. producers credit with helping them to maintain their world-leading market share.

In a Capsule: NIST Services

NIST measurement services and standards-related activities open the way to competitive advantages: higher quality products, more reliable and more flexible processes, fewer rejected parts, speedier product development, more efficient market transactions, higher levels of interoperability among machines, factories, and companies. The ultimate U.S. reference point for measurements with counterparts throughout the world, NIST supplies companies—and even entire industries—with the equivalent of a common language needed in every stage of technical activity.

NIST provides:

- About 1,300 different Standard Reference Materials (SRMs) that are certified for their specific chemical or physical properties. SRMs are used to: help develop accurate methods of analysis; calibrate measurement systems; and assure the long-term adequacy and integrity of measurement quality assurance programs. For example, U.S. steel makers rely on more than 125 NIST SRMs to ensure the quality of starting materials and finished products.
- More than 50 electronic databases in chemistry, physics, materials, building and fire research, speech recognition software, and electronics. For 30 years, NIST's Standard Reference Data Program has provided well-documented numeric data to scientists and engineers for use in technical problem solving, research, and development. Recommended values are based on data that have been extracted from the world's literature, assessed for reliability, and then evaluated for the preferred values. To improve access and ease of use, a growing share of evaluated data and other technical information is being placed on line, accessible via the Internet through the NIST Office of Electronic Commerce in Scientific and Engineering Data (http://physics.nist.gov/PhysRefData/contents.html).
- More than 500 different calibrations, special tests, and measurement assurance programs. Ranging from calibrations of gage blocks and thermocouples to tests of form-fitting software used in coordinate measuring machines, these services underpin a measurement transfer system critical to manufacturing and assembly processes.
- Standards-related information and assistance to about 20,000 organizations and individuals every year.

Measurement needs are growing and diversifying in every area of manufacturing. In precision manufacturing—a label that applies to a growing portion of the discrete parts industry—dimensional tolerances are shrinking to ever smaller fractions of a split hair. Meanwhile, the shapes of parts and products are growing more complex.

In the continuous-process industries, manufacturers must continuously raise the threshold for levels of selectivity and specificity. Indeed, all manufacturing industries are being driven to improve processes, reduce waste, and raise quality. At the same time, emerging technologies present tantalizing prospects for novel products and processes, but they also introduce new measurement challenges that must be mastered before these opportunities can be fully realized.

Aligned with Industry Needs

Research and services performed by NIST's Measurement and Standards Laboratories stretch along the full spectrum of manufacturing activities—from the processing of raw materials into feedstocks to final product inspection to marketing and after-sales support. Its seven component laboratories are aligned with major industrial sectors or key technology clusters:

- Manufacturing Engineering,
- Electronics and Electrical Engineering,
- Materials Science and Engineering,
- Chemical Science and Technology,
- Building and Fire Research,
- Information Technology, and
- Physics.

All work closely with U.S. industry, and they participate in its technology planning activities, such as the National Electronics Manufacturing Initiative, Integrated Manufacturing Technology Roadmapping Initiative, National Technology Roadmap for Semiconductors, the U.S. chemical industry's Technology Vision 2020, and the National Plan for Building and Construction R&D.

Much work is done collaboratively with partners from U.S. companies, universities, and government laboratories. More than 10 NIST-led consortia are addressing manufacturing-technology needs and processing issues. Aims of these collaborations range from improving the machinability of ceramic parts to developing prototype standards and interfaces that allow diverse packages of manufacturing engineering software to work together. (See the list of consortia on p. 14.)

ATP: Pushing the Envelope

"... [T]he program is an effective means of promoting high-risk research that enables large and small U.S. companies to advance technologies which hold promise for broad economic impact."

—Ed Wasserman, President (1999)
American Chemical Society

> The ATP helps bridge the gap between the laboratory and the marketplace.

Since its start in 1990 as a small experimental program to promote "commercializing new scientific discoveries rapidly" and "refining manufacturing practices," the ATP has emphasized innovation in industrial processes. Advances in manufacturing technology and leaps in process-related capabilities are central themes.

The ATP helps bridge the gap between the laboratory and the marketplace. It stimulates partnerships among companies of all sizes, universities and the rest of the R&D enterprise. Over half of ATP awards have gone to individual small businesses or to joint ventures led by a small business. More than 140 universities are participating in ATP projects as either joint-venture participants or subcontractors.

By design, the program encourages businesses to focus on the long term, to look beyond the next one or two product cycles and to invest the resources required to convert promising, but unproven, emerging technologies into new products and manufacturing methods. This focus is a needed counterbalance to recent private-sector trends.

Companies are concentrating more and more of their research and development efforts within the envelope of the predictable, the incremental, the nearly immediate. As a result, "less and less" of private-sector R&D spending, the Council on Competitiveness reported recently, "is spent on longer range research—the kind of research that ensures continued economic growth."

In competitively selected projects funded by the ATP, companies pursue:

- pathbreaking technologies that, down the road, have the potential to spawn new commercial markets or enable revolutionary capabilities;
- infrastructural technologies that hold promise for improving the research and development, production, or business performance of entire industries; and
- multiple-use technologies anticipated to have many distinct applications.

Competitions

ATP projects are selected through competitions open to proposals from all areas of technology. The program relies on private industry to evaluate technological opportunities and propose solutions. Proposed projects are evaluated and ranked in competition with others in the same technology area. The program provides funding for R&D (but not for product development) by both individual companies and industry-led joint ventures.

> With industry, ATP regularly surveys the technology horizon for long-term opportunities that ... may pay significant dividends in terms of U.S. competitiveness and economic growth.

Since its first competition in 1990, the ATP has been proven successful in catalyzing the development of powerful and innovative new technologies in a broad range of fields, including several that concentrate largely on manufacturing issues:

- **Manufacturing Composite Structures:** Reduce the high initial costs of using advanced composite materials—now largely limited to military and sports applications—and enable use of these strong, lightweight, durable materials in large-scale commercial applications, such as automobiles and bridges.
- **Technologies for the Integration of Manufacturing Applications:** Develop and demonstrate technologies needed to create affordable manufacturing software applications that can be rapidly integrated and reconfigured, ultimately leading to systems that can adjust automatically to changing conditions and requirements.
- **Motor Vehicle Manufacturing Technology:** Foster innovations in manufacturing technologies to strengthen capabilities throughout the entire automotive production chain, including more versatile equipment, better control and integration of processes, and greater operational flexibility at all levels.
- **Materials Processing for Heavy Manufacturing:** Develop and demonstrate innovative materials-processing technologies that will help U.S. heavy manufacturing companies make longer lasting, more reliable, and more efficient products—for example, truck engines that need overhauls only after 1.6 million kilometers (1 million miles) or drive trains that require only half as much maintenance and repair.
- **Catalysis and Biocatalysis Technologies:** Develop the tools, abilities, and theoretical insight to identify, design, and implement new catalytic and biocatalytic processes and catalyst manufacturing techniques of major economic importance to chemical producers and other catalyst users.
- **Microelectronics Manufacturing Infrastructure:** Develop new infrastructure technologies in materials, design, manufacturing, and testing; enable strategic advances in semiconductor chips, processes, packaging, and board interconnections. Industry roadmaps identify these technologies as posing barriers to the smaller, lighter, faster, and more cost-effective microelectronic products demanded by world markets.
- **Photonics Manufacturing:** Foster research and development leading to the packaging technologies, simulation and modeling tools, processing methods, equipment, and instrumentation necessary for cost-effective, high-volume production of optoelectronic parts and products.

- **Selective-Membrane Platforms:** Develop agile, robust membrane-based separations technologies that are highly selective, but achieve high throughput. These technologies would lead to environmentally benign, economically efficient manufacturing capabilities in industries ranging from pharmaceuticals and medical diagnostics to automobile parts, consumer electronics, and clothing.

With industry, ATP regularly surveys the technology horizon for long-term opportunities that, down the road, may pay significant dividends in terms of U.S. competitiveness and economic growth.

MEP: Building Manufacturing Muscle

"The ... entire national Manufacturing Extension Partnership [is] an important resource for helping smaller manufacturers achieve the kinds of world-class gains formerly limited to large companies. Their focus on value adding activity on the shop floor is exactly right."

—Richard Schonberger, author,
World Class Manufacturing: The Next Decade

> MEP currently has more than 400 locations serving smaller manufacturers in all 50 states, the District of Columbia, and Puerto Rico.

NIST's Manufacturing Extension Partnership was created to fill gaps in technical services that impede the modernization of the nation's more than 385,000 smaller manufacturing businesses, factories with fewer than 500 employees. Typically employing fewer than 50 people, these establishments have generated about three-fourths of all new manufacturing jobs over the last two decades. They now account for over half of U.S. manufacturing output.

Yet, many smaller manufacturers have been slow to adopt modern production technology and practices. Productivity growth has trailed that of their larger counterparts, creating a gap that threatens future competitiveness. Many factors—from limited investment capital to lack of information to pressing day-to-day demands on management—underlie this widely recognized weakness in a strategically important part of the nation's industrial base. Until very recently, however, this problem drew only a small, fragmented response.

Through the MEP network of local extension centers, each one linked to public and private organizations with complementing expertise, smaller manufacturers now have access to comprehensive sets of technology and business assistance. MEP centers have provided services to more than 80,000 smaller manufacturers. About half of these client firms employ fewer than 50 people, and nearly two-thirds employ fewer than 100. By the year 2001, MEP anticipates that affiliated centers will be delivering technical assistance to 10 percent of the nation's smaller manufacturers each year.

MEP currently has more than 400 locations serving smaller manufacturers in all 50 states, the District of Columbia, and Puerto Rico. The young network is still maturing, but it quickly is becoming recognized as a vital federal-state partnership that is helping thousands of small firms improve competitiveness, increase profits, and enhance productivity.

"Systematic evaluation studies have confirmed that the MEP is having a positive effect on businesses and the economy," a researcher from the Georgia Institute of Technology's School of Public Policy recently reported. For example, the California Manufacturing Technology Center recently reported a return on investment of nearly 300 percent during a three-year period. The center also reported that as a result of collaborations in 1998, 131 client firms created or retained more than 1,300 jobs, increased revenues by $56.3 million, and created tax benefits totaling almost $34 million to local, state, and federal governments.

Companies that credit MEP assistance with subsequent improvements in performance include:

- *The Montalvo Corporation, a Portland, Maine, manufacturer of tension systems for equipment in the converting and packaging industries.* Because the company relies heavily not only on its manufacturing and servicing equipment, but also its business computer systems, Montalvo asked the Maine Manufacturing Extension Partnership to help it determine whether it was at risk because of the year 2000 (Y2K) computer problem. "Thanks in large part to the MEP Y2K tool, we are now as confident as we can be that the year 2000 bug will not interfere with our operations," said Ed Montalvo, president and one of the company's managing directors.

- *Leonhardt Plating, a family-owned-and-operated electroplating business located in Cincinnati, Ohio.* Looking for a more cost-effective way to coat metals, the 20-employee company contacted its local MEP affiliate—the Miami Valley Manufacturing Extension Center (MVMEC)—to help it reduce wastes. After conducting an operational assessment, MVMEC advised Leonhardt to install timed flow controls, countercurrent rinses, and other waste-minimization equipment. With these changes, monthly water consumption for processing dropped from 500,000 gallons to about 160,000 gallons, saving Leonhardt more than $5,000 annually. Equally dramatic was the drop in chrome use—from 700 pounds to 400 pounds annually—with no change in output. In addition, the company developed a new process that eliminates discharges to the metropolitan sewer district.

Funded with federal, state, and local dollars, all MEP affiliates are non-profit organizations. All affiliates are locally staffed and operated—organized to be responsive to the particular technical needs of an area's manufacturing sector.

As the federal partner, NIST concentrates on making the whole greater than the sum of the parts. For example, NIST works to strengthen system capabilities in areas strategically important to smaller manufacturers.

Networkwide MEP initiatives include:

- Sustainable Manufacturing. With affiliates across the country, the U.S. Environmental Protection Agency, and other partners, MEP is developing and testing tools that will help manufacturers to reduce waste, emissions, and inefficiencies as well as the burdens of complying with environmental regulations. In center-conducted assessments, difficulties encountered when responding to environmental regulations and permitting requirements often rank among the top challenges cited by manufacturers.

- Technology and the workforce. In MEP's assessment of challenges facing smaller manufacturers, workforce training is second only to the constant requirement to reduce costs while increasing quality. Human resources projects now account for 10 percent of all MEP technical assistance activities. MEP staff and affiliates are working with the U.S. Department of Labor, community colleges, and other organizations to further build system-wide capabilities to help firms upgrade worker skills and devise high-performance workplace strategies most appropriate for their businesses and workforces.

> NIST works to strengthen system capabilities in areas strategically important to smaller manufacturers.

Anticipating needs and challenges, MEP also is designing new initiatives to help smaller manufacturers acquire the capabilities necessary to compete successfully in the 21st century. Current trends indicate that the supply-chain optimization efforts of major original equipment manufacturers will be especially critical to the long-term performance and business health of smaller manufacturers.

MEP is working with smaller manufacturers to help them gain the organizational, logistical, and operational skills required to perform effectively and profitably in the emerging era of supply-chain-centered competition.

Baldrige National Quality Program: An Agent for Change

"More than any other program, the Baldrige Quality Award is responsible for making quality a national priority and disseminating best practices across the United States."

—Council on Competitiveness, *Building on Baldrige: American Quality for the 21st Century*

Since its creation in 1987, the Baldrige National Quality Program has played an important role in helping the United States regain its competitive edge and its world-class quality ranking among nations. But, the competitive race is far from being won. For manufacturers, in particular, quality now is a mandate, not an option. Companies worldwide recognize the competitive advantages achieved through quality and performance excellence. To attain and retain market leadership in the next century, U.S. companies will have to improve continuously.

Of the 37 companies to date that have won the Baldrige Award, 26 are manufacturers. These include some of the nation's largest firms, such as Motorola and the Eastman Chemical Co., and smaller manufacturing businesses, such as Trident Precision Manufacturing and Wainwright Industries, parts and assembly suppliers with payrolls of fewer than 300 people. For all, the Baldrige Award process has proved to be an effective tool for continuous improvement.

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"The [award] criteria became our road map to success," says Nicholas Juskiw, Trident's chief executive officer, "and every year our metrics have improved, our costs have been lowered, and customers and employees have become more satisfied. Using the criteria, we implemented systematic approaches in those areas where none existed."

Following the Baldrige guidelines continues to pay performance improvement dividends to firms that maintain their commitment to quality. Consider a few examples:

- Nearly 25 percent of Eastman Chemical Co.'s (1993 manufacturing winner) sales come from new or improved products developed in the last five years.
- Since winning the Baldrige Award in 1988, Globe Metallurgical, Inc. (1988 small business winner) has experienced a 204 percent increase in revenues and a 310 percent increase in profits.
- Wainwright Industries, Inc. (1994 small business winner) has reduced its customer reject rate by 91 percent and cycle time by more than 90 percent. It used the Baldrige framework to drive more than 10,000 quality and process improvement suggestions implemented each year since 1994.

Thousands of companies have not applied for the national award but use the Baldrige Award application to take measure of their own operations. More than 1.7 million Baldrige Award criteria have been distributed. Annually updated and enhanced by leading quality and business experts, the criteria serve as very functional tools—as scorecards to size up performance and identify opportunities for improvement.

Further fueling the drive for quality improvement, the Baldrige Award has become a widely emulated model—the standard for performance excellence. Not only do more than 40 states have award programs, but also, nearly 60 international quality awards have been established. Most resemble the Baldrige Award, including one launched by Japan in 1996.

NIST is mapping out ways to strengthen awareness of the award program and criteria among smaller manufacturing businesses and other similarly sized firms. As Trident and Wainwright demonstrate, such companies can benefit greatly by implementing the Baldrige framework.

Points of Emphasis

With industry's guidance, NIST is stepping up efforts in key technology areas likely to have a major impact on future manufacturing capabilities. On behalf of U.S. industry, it also is intensifying and broadening its technical activities in the international standards arena, which greatly influences the ability of the nation's manufacturers to sell their products in foreign markets.

Standards and Trade

Make competitively priced, quality products that appeal to consumers and commercial success is sure to follow. Perhaps not. A key variable missing from this formula is conformance of manufacturing and product testing processes with the standards of the prospective markets. Without provable conformance, a manufacturer's shipment of products may, quite literally, be left sitting on the customs dock.

Technical barriers to trade are emerging as chief obstacles to achieving a "level playing field" for international commerce. Increasingly, access to markets is dictated by sophisticated measurements, standards, testing and certification requirements, directives, and other technical prerequisites that often are incompatible with U.S. standards. Eliminating these barriers and incompatibilities could boost the annual volume of U.S. exports by $20 billion or more.

NIST is expanding its work with the private sector, through the American National Standards Institute and other voluntary standards organizations, to promote international acceptance of U.S. standards. One outcome of this partnership is the NSSN, a World Wide Web-based service that provides information on national and international standards, including those under development. With ANSI and ACIL (formerly the American Council of Independent Laboratories), NIST is working toward a system for recognizing the competence of testing and calibration laboratories, thereby enabling worldwide acceptance of their test and calibration reports. Such a system would deliver a very large, practical benefit: "one-stop-shopping" for U.S. manufacturers. Products would be tested only once but accepted everywhere around the globe.

Information Technology

The nation's businesses now spend more on information technology than they invest in factories, vehicles, or any other type of equipment. Information technology investments may not yield full value, however, as targeted performance improvements and competitive advantages fall short of expectations. The reason: Companies lack the tools to flexibly integrate processes, systems, and suppliers on regional, national, and even global scales.

NIST and its partners have set out to eliminate the large disparity between "what is" and "what can be" for information technology. In the area of electronic commerce, NIST is contributing to efforts to ensure the security of on-line transactions and to overcome a host of other technical obstacles that now prevent the market for electronic commerce services and applications from achieving its vast potential.

STEP on it!

And researchers in its Systems Integration for Manufacturing Applications—or SIMA—program are collaborating with teams from industry to develop prototype information exchange standards and interfaces for communicating product and process data among various manufacturing activities: design, process planning and scheduling, production, quality control, and others. The goal of one project, for example, is to develop a neutral process specification language—the means to describe elements of the manufacturing process so they can be understood and acted on by computers and software applications made by different suppliers.

The SIMA project leverages and extends the international Standard for the Exchange of Product Model Data, or STEP. Officially known as ISO 10303, STEP is an evolving "super standard" that is becoming the universal language for electronically exchanging product data. NIST pioneered the development of STEP, and it continues to contribute to its technical development and to broadening the range of capabilities that the standard enables.

NAMT: A Distributed Testbed

At NIST's National Advanced Manufacturing Testbed, teams of researchers also are working to solve measurement and standards issues that impede companies and industries from making the most of their information technology, individually and collectively.

The NAMT is a distributed, multiproject testbed built on a state-of-the-art, high-speed computing and communications infrastructure—the research counterpart to the distributed and virtual enterprises envisioned for 21st-century manufacturing. It links people—as well as specialized facilities and resources—at sites around the country as they tackle process-specific challenges and opportunities.

> The NAMT is a distributed, multiproject testbed built on a state-of-the-art, high-speed computing and communications infrastructure....

Sixteen projects are under way at the testbed. In one, a NIST-led consortium is developing the basis for virtual machine tools and inspection machines that behave just like their factory-floor equivalents, making it possible to produce parts that consistently meet specifications on the first try.

In another, collaborating scientists and engineers are building a Computer-Integrated Construction Environment. This will enable seamless, real-time exchanges of information among all of the many and varied participants in a construction project.

Infrastructure, Infrastructure, Infrastructure

NIST's Information Technology Laboratory attends to a broad range of needs and issues affecting the quality, reliability, utility, and flexibility of today's and tomorrow's information technology products. In its infrastructural role, the laboratory concentrates on developing tests and test methods for technologies and advanced applications that are still in the early stages of development. Ongoing projects support industry efforts in areas ranging from human-machine interface technologies to automated software diagnostics to computer security.

> NIST's work on sensors and control systems is multifaceted.

Efforts to improve the utility and capabilities of information technology cut across all of NIST. For example, projects under way in the ATP focused program on Technologies for Integrated Manufacturing Applications aim to bridge the performance-limiting information gap that separates design and high-level management information systems from factory-floor control systems. Emphasis is on mid-level information systems known as manufacturing execution systems (MES). Results of the ATP focused program projects will contribute to the development of real-time, "plug-and-play" MES applications, built largely with standardized, easily integrated components.

Another ATP focused program addresses the often costly limitations of the current craft-like methods for designing, producing, and assembling software-based systems. Only about 15 percent of today's installed software base consists of commercially available, off-the-shelf applications. Customized systems, which are beyond the budgets of most businesses, account for the rest. Not only are these one-of-a-kind systems expensive, but they also tend to be monolithic. Upgrades and other modifications are arduous, time-consuming tasks, requiring additional expenditures and, often, impeding a company's ability to respond rapidly to market changes or other factors.

The Component-Based Software focused program is fostering development of technologies that will enable systematically reusable software components—relatively small, carefully engineered software elements suitable for a broad array of applications. With such technologies, software companies could build specialized components that can be sold to systems integrators and custom builders, who would combine them with other, largely purchased, off-the-shelf components to create high-quality custom applications.

Sensors and Control Systems

Driven to improve quality and lower costs, manufacturers are loathe to leave anything to chance. Today, it is not unusual for a single production line to have more than 40 sensor points. In fact, one in five manufacturers responding to a recent survey reported monitoring more than 100 points on a line.

Sensors, the "eyes and ears" of manufacturing, will continue to grow in importance, as will the need to develop systems that gather, analyze, and effectively act on sensor-gathered information in real-time—averting process upsets, defects, and down-time.

Supporting both the discrete manufacturing and continuous-process industries, NIST's work on sensors and control systems is multifaceted. Some projects exploit new technologies and capabilities—such as micromachining—and recent discoveries—such as the phenomenon of giant magnetoresistance—to develop advanced measurement tools.

With an eye on improving chemical processing capabilities, NIST semiconductor and chemistry researchers have designed and built arrays of microscopic hot plates that are machined into the surface of a silicon chip. Research efforts are directed toward developing methods and materials that will allow these sensor arrays to be tuned to detect and measure the concentrations of different gases, reporting the results instantaneously. Today, detection and measurement of individual or multiple gas species requires relatively expensive analytical instruments, with response times ranging from seconds to hours.

Scientists in NIST's Measurement and Standards Laboratories also are investigating innovative sensor-based approaches to monitoring key variables in other industrially important processes, including welding, casting, steelmaking, thermal processing, thin-film deposition, photochemistry, atomization of alloy powders, and inspection. Improved process control is the overriding objective.

Cutting across all these areas—and more—is a NIST-facilitated effort to develop interface standards for smart sensors and actuators—devices that detect, interpret, and respond to changing operating and environmental conditions. Working with more than 25 companies, NIST spearheaded development of an

Institute of Electrical and Electronics Engineers standard that permits communication between and among sensors linked to a control network. By enabling interoperability, the new hardware-independent standard simplifies systems integration tasks. It also helps to extend intelligence to the sensor and actuator nodes of control systems. Because of the lack of a common interface, use of smart sensors and actuators in manufacturing systems has lagged behind growing opportunities for improving measurement and control.

Open Architecture

The Measurement and Standards Laboratories also have been instrumental in fostering an emerging industry consensus on open-architecture standards for machine tool controllers. Agency researchers built the NIST enhanced machine controller, or EMC, to serve as a vehicle for developing and fostering adoption of standardized interfaces for the programs, devices, and communication networks that are linked to controllers in modern factories.

Such links would enable varied assortments of hardware and software to work together—without first engaging in what has typically been a herculean, one-of-a-kind systems integration effort. The value of this sought-after interoperability was demonstrated in trials of the EMC at General Motors' Pontiac, Mich., Powertrain Division; a Boeing plant in Auburn, Wash.; and a one-man machine shop outside Baltimore.

Interface specifications that NIST develops are offered to industry as the starting points for standards. Also to further progress toward a widely adopted open controller architecture—long on the wish list of U.S. manufacturers—NIST will develop measurements and tests for validating prototype standards, focusing on priority applications identified with the guidance of a NIST consortium and other industry groups. The collaborators will develop tests and tools that will help controller manufacturers and software vendors ensure that their products conform with standards—a role similar to the one that NIST already performs for STEP, the international product data exchange standard. Recently, *American Machinist* included the EMC project among five research efforts that the magazine anticipated as "likely [to] have significant relevance in shaping the future of machine-tool technology."

Semiconductors, MEMS, and Nanotechnology

"Smaller, faster, cheaper." These words have been repeated like an unending chorus by the nation's electronics firms since the industry's earliest days. The miniaturization trend now cuts across industries—existing ones and those still edging toward the market. NIST research and services are important to the technological performance of both.

> The Laboratories also have been instrumental in fostering an emerging industry consensus on open-architecture standards for machine tool controllers.

Better Chips

For more than 40 years, the NIST Laboratories have provided fundamental measurement support to the U.S. semiconductor industry. Tools and services resulting from this collaboration have reduced defects and increased yields—returns that have repaid the research investment many times over.

Today, NIST manages the National Semiconductor Metrology Program, which supports more than 35 research projects. These projects are designed to help meet the priority measurement needs of U.S. chip manufacturers and their suppliers as they race to squeeze more and smaller devices on a sliver of silicon. Among the program's most recent accomplishments is a proposed measurement reference that is expected to help semiconductor manufacturers reliably measure critical chip features equivalent to about 1/500th the width of a human hair. NIST's technical efforts also are furthering industry's push toward shorter-wavelength photolithography, while contributing to development of alternative—and still experimental—methods for printing even smaller integrated circuit patterns on future-generation chips.

In addition, technological advances enabled by the ATP are helping to keep the U.S. semiconductor industry on track as it pursues future manufacturing targets. With timely assistance from the ATP, for example, Diamond Semiconductor Group succeeded in developing technology that attracted outside capital from Varian Associates. The partnership yielded a prototype ion-implant machine and, in 1996, accomplished an “industry first”—successful ion implantation of a 300 millimeter wafer, or two-and-a-half times larger than the industry standard then.

NIST also is providing technical assistance to the nation’s data-storage industry, which is racing to squeeze more information onto disks and tapes even as it explores the potential of experimental storage technologies. For example, a NIST-designed instrument—called SEMPA, for scanning electron microscope with polarization analysis—can image the magnetic microstructure of materials. Surface analyses done with the instrument have pointed the way to improvements in methods for making thin-film magnetic storage devices as well as those that exploit the giant magneto-resistance effect. In addition, NIST and collaborators are using SEMPA to study how the magnetic microstructure of materials influences the efficiency of transformers used in motors and electric power generators.

MEMS

Following in the wake of integrated-circuit and information-storage technologies, microelectromechanical systems (MEMS), which combine electronic and mechanical components in the same miniature device, are just beginning to make their own waves in markets for high-technology products. Today, MEMS applications are limited to a few types of sensors, but the market is projected to grow to between $3 billion to $14 billion early in the next century. Growth rates are predicted to be comparable to those for microelectronics over the last several decades. MEMS applications are expected to mushroom in a variety of areas—manufacturing, transportation, healthcare, military systems, communications, testing and instrumentation, environmental monitoring, and others.

To speed the technology’s maturation and to foster innovation, NIST has created a design library for the growing MEMS research community. It also helped to launch a service that enables designers of experimental devices to use commercial silicon foundries for all but the last step in MEMS fabrication. One motivation for the service was to enlarge the pool of researchers developing MEMS technologies. It provides universities and other innovative organizations with access to otherwise unaffordable processing capabilities.

NIST also is developing ways to measure stress, strain, elasticity, and other mechanical properties of thin films used in making MEMS. While integrated circuit test methods for measuring electrical properties like resistance and voltage are well advanced, testing protocols for mechanical properties are in their infancy. One goal is to develop models for predicting the thermal, electrical, and mechanical behavior of various MEMS designs.

So far, NIST researchers have collected designs for nearly 70 test structures from universities and a non-profit semiconductor processing facility. They now are evaluating the structures for their ability to measure specific mechanical properties. The best designs, along with testing procedures, will be available through electronic libraries, enabling MEMS manufacturers to tailor reliable production control systems that are traceable to NIST standards.

In the biotechnology field, innovative micro-instrumentation technologies are beginning to prove their mettle. For example, Affymetrix, winner of an ATP award, has modified semiconductor manufacturing techniques to make DNA diagnostic arrays—powerful tools that can be used to analyze thousands of genes at a time. Originally ignored by potential sources of capital, Affymetrix introduced the first “biochip” in 1996, launching what some expect to be a revolution in diagnostic medicine and biomedical research.

Smaller Still

Manufacturing now appears headed toward the domain of molecules and even atoms. The development of products with features and components smaller than 100 nanometers—the threshold at which the laws of conventional physics begin to break down—is being pursued assiduously in laboratories around the world. At the same time, miniaturization trends in the semiconductor manufacturing industry are converging on the 100 nanometer barrier, where important challenges and interesting quantum effects await.

> One goal is to develop models for predicting the thermal, electrical, and mechanical behavior of various MEMS designs.

Nanotechnology, however, is not simply a continuation of miniaturization trends and the further scaling down of conventional structures and materials. Rather, it entails assembling materials and structures with aggregates of atoms and molecules. Such molecular-scale manufacturing is expected to lead to products that exploit new properties and phenomena, resulting in new capabilities or performance advantages.

Not surprisingly, manufacturing on this scale presents a host of new measurement needs. NIST's Measurement and Standards Laboratories already have begun to address them. Its one-of-a-kind molecular measuring machine has been placed into service, while it continues to undergo refinements. The NIST-built instrument is designed to measure, with unprecedented accuracy, relative distances between molecule-sized features situated anywhere within a square 50 millimeters on a side—a range 250,000 times greater than that of most scanning tunneling microscopes. An executive of an instrument manufacturing company described the new NIST measuring machine as "ultimately the holy grail in semiconductor and hard disk manufacturing."

Related efforts aim to increase the usefulness of the multitude of scanning probe microscopes (SPMs). SPMs include scanning tunneling microscopes, atomic force microscopes, and a growing repertoire of related instruments with sharp tips, often needle-like in shape. They are best known for their ability to generate three-dimensional images of specimens in atomic detail but, depending on the design, SPMs also are used to analyze a wide range of physical and chemical properties, from magnetism to temperature to hardness.

Microelectronics firms and others that make products with ultraminiature, high-precision components are pressing SPMs into practical service. However, few measurement standards exist for these instruments, which means results obtained with one instrument cannot be compared objectively to those obtained with another instrument of the same type. The NIST laboratories are developing tools that will enable SPM users to make highly accurate, quantitative measurements with their instruments, a must for industrial applications.

One project, now under way at NIST's National Advanced Manufacturing Testbed, has set out to develop measurement references that are derived directly from nature's own geometry—the regular spacings in crystal lattices. The aim is to fabricate atom-based artifacts with almost geometrically perfect, nanometer-scale features. Used to calibrate instruments, such tools would minimize uncertainty and ensure high levels of confidence within and across companies.

Other work focuses on fabrication techniques; nanometer-level control, manipulation, and positioning; instrumentation; and theory. In one recent accomplishment, NIST scientists and colleagues from Harvard University used neutral atoms, instead of light, to create patterns in silicon. The new method offers the promise of one day manufacturing integrated circuits and other devices with components about 10 times smaller than is possible with light-based lithography.

The same NIST team also was the first to fabricate permanent nanometer-sized structures by using a standing wave of laser light to deposit chromium atoms in series of regularly spaced lines. The researchers have since extended their technique of laser-focused atomic deposition to make two-dimensional arrays of nanodots, a capability that may lead to new types of measurement tools for manufacturing on molecular scales.

NIST Programs:

For more information, visit
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NIST Manufacturing-Related Consortia

Ceramic Machining Consortium

Develops cost-effective production processes for grinding components made from advanced, structural ceramics, such as silicon nitride and silicon carbide.
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Ceramic Processing Characterization Council

Develops new measurement-based strategies for ensuring reliable manufacturing by working with the U.S. ceramics industry to develop the measurements and standards infrastructure for ceramic particulate systems.
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Coatings Service Life Prediction

Develops test methods to predict quickly and reliably the service life of painted products exposed to the elements in order to help the U.S. paint industry get better products to market more quickly.
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Flowmeter Installation Effects

Supports research in fluid flow measurements to help industry understand, evaluate, and assess flowmeter performance under non-ideal flowmeter installation conditions.
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Monolithic Microwave Integrated Circuits

Develops metrology for design and manufacture of monolithic microwave integrated circuits, especially measurement methods and standards to reduce testing costs.
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NIST-EPRI Ultrasonic Flow Meter Testing Program

Provides guidelines to improve flow measurements in industrial environments. NIST will assess ultrasonic flowmeters from the consortium members by testing their commercially available, clamp-on type, time of travel ultrasonic flowmeters in both ideal and non-ideal pipe flows.
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Optical Properties of Materials

Develop new standards and critically evaluated data on the optical properties of materials that are important for evolving optical industries and manufacturing processes.
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Orthopedic Accelerated Wear Resistance

Helps shorten development and approval time for new orthopedic implants by identifying test methods with the greatest promise for accelerated screening of materials for wear resistance.
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Machine Tool Performance Models and Machine Data Repository

Develop tools to replace actual machining and inspection of parts during prototyping with virtual machining and virtual inspection modules incorporated into a CAD/CAM system. These tools include data structures and low-order machine models that represent actual machine behavior; mathematical representations of actual part geometry, including dimension and form errors; virtual machining algorithms; virtual inspection algorithms; standardized data formats; and remotely accessible machine data repositories.
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Manufacturing-Related Facilities and Testbeds

Materials, Materials Processing, Surface Treatment

Electron Beam Ion Trap
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Materials Science X-ray Beamlines
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Powder Characterization and Processing
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Synchrotron Ultraviolet Radiation Facility (SURF III)
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Manufacturing Applications of Information Technology

Advanced Manufacturing Systems and Networking Testbed
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Engineering Design Testbed
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National Advanced Manufacturing Testbed

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Nanomanufacturing of Atom-Based Standards
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Characterization, Remote Access, and Simulation of Hexapod Machines
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Radioactive Source Manufacturing
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Interface Data Standards for Real-Time Construction Site Metrology
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Interface Standards and Internet Technologies for Robotic Arc-Welding
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Virtual Die Design for Information-Based Metal Forming
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Internet Commerce for Manufacturing
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Verification of Information Technology Solutions for Small and Medium Size Manufacturing Enterprises
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Open Virtual Reality Testbed
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Machining and Inspection

High-Speed Machining Testbed
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Next Generation Inspection System Testbed
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Intelligent Systems

Integration Testbed for Mobility
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Intelligent Systems Integration Testbed for Large-Scale Manufacturing and Construction
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Microelectronics and Magnetics

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Radiation Processing

Design, Manufacture, and Calibration of Radioactive Sources for Medical Therapies
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Medical-Industrial Radiation Facility
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Thermal Processing

Rapid Thermal Processing Testbed
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Other Infrastructural Support Facilities

Acoustic Anechoic Chamber Facility
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